Development of a Smart Cooling and Fertigation System for Strawberry Cultivation in Tropical Lowland Greenhouses

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Article Info

Abstract

Strawberry cultivation in tropical lowland regions faces major challenges due to excessive heat, high humidity, and poor root zone temperature regulation, often leading to low fruit quality and inconsistent yields. This project aims to address these limitations by integrating environmental optimization with smart agricultural technology tailored for tropical greenhouse applications. The main objective is to develop a sustainable, IoT-enabled fertigation and microclimate control system for strawberry cultivation in lowland Malaysia, focusing on improving yield, fruit sweetness, and plant resilience. A comprehensive review was conducted on critical environmental parameters like temperature, humidity, light intensity, CO_2 levels, and electrical conductivity combined with a study of recent innovations in precision agriculture. Based on this review, a prototype system is proposed featuring solar-powered chillers, automated misting, root zone cooling, and fertigation component controlled by ESP32 microcontrollers. The system includes real-time sensor feedback and wireless control to maintain optimal growing conditions. The proposed system will be developed at Politeknik Sultan Haji Ahmad Shah (POLISAS) and will be tested in a real-world setting at FELDA Bukit Sagu 2, a rural farming community in Kuantan. Preliminary simulations from review suggest a greenhouse temperature reduction of 4°C–6°C and improved root zone stability, aligning with recommended growth thresholds. These improvements are expected to enhance strawberry size, sweetness (Brix value), and shelf life. The novelty of this project lies in its context-specific combination of smart cooling and fertigation technologies in a modular, scalable design suitable for low-resource farming environments. It bridges academic innovation and practical agriculture, supported by sustainable energy integration and data-driven control. The project idea has gained early recognition in institutional R&D and is positioned for further collaboration with agricultural research bodies (e.g., MARDI), smart farming startups, and rural development agencies. With continued development, the system offers potential as a replicable model for tropical horticulture, supporting Malaysia's goals for agrotechnology innovation and food security.

1. Introduction

Strawberries are among the most economically valuable horticultural crops, widely cultivated for their high nutritional content, market demand, and versatility in processing. Traditionally grown in temperate climates, strawberries are now increasingly cultivated in tropical lowland regions, particularly through controlled-environment agriculture (CEA) such as greenhouses [1]-[2].

However, adapting strawberry production to tropical lowlands presents unique challenges. Unlike temperate zones where natural climatic conditions support growth, tropical regions experience elevated temperatures, high humidity, and fluctuating light conditions that can impair flowering, reduce fruit quality, and increase disease incidence [3]-[4]. These stressors are especially harmful to photoperiod-sensitive and cold-requiring cultivars, often resulting in poor yield and shortened shelf life.

To ensure successful cultivation in such climates, precise environmental control is essential. Optimizing microclimatic variables such as air temperature, humidity, root zone temperature, and light exposure can directly influence flowering, fruit development, sweetness, firmness, and overall marketability [5]-[6]. The integration of sensor technologies and automation into greenhouse systems provides promising solutions for real-time monitoring and adaptive management [7]-[8].

Climate variability in tropical areas also affects the stability of production systems. Fluctuations in temperature and humidity not only influence plant physiology but also impact pest and disease dynamics, often necessitating increased chemical interventions which may not be sustainable. Studies by [9], utilizing multivariate copula analysis, highlight how temperature anomalies primarily drive yield fluctuations, emphasizing the need for precise environmental management strategies.

Traditionally, strawberry cultivation in these regions relies heavily on open-field and low-tech plastic house systems, which lack the capacity to regulate environmental parameters effectively. Consequently, farmers experience high yield variability, increased operational costs, and compromised product quality. As a response, innovative indoor and greenhouse cultivation techniques have been explored, incorporating advanced environmental control strategies to stabilize and enhance production.

In recent years, the integration of smart technologies including IoT sensors, automated climate control systems, and predictive models has gained prominence as an effective approach to overcoming environmental challenges. For instance, studies by [7] introduced inexpensive sensor networks enabling real-time monitoring of soil moisture, temperature, and humidity, facilitating timely interventions that maintain optimal growth conditions. Similarly, the application of machine learning models, such as the RL-Informer developed by [5], demonstrates how AI-driven systems can predict environmental fluctuations and adjust control mechanisms proactively.

Furthermore, research has shown that precise environmental control can be achieved through a combination of technological tools. [10] demonstrated that accurate regulation of root zone temperature (RZT) and light intensity using sensors and automated systems significantly improved strawberry flowering and fruiting in hydroponic systems. This underscores the potential for integrating sensor networks with controlled environment agriculture (CEA), including greenhouses, aeroponics, and hydroponics, to combat climate variability.

Regional case studies reveal that in Malaysia and Japan, controlling the environment via greenhouse structures equipped with automated systems has resulted in more stable yields and better fruit quality outcomes. [1] compared the approaches, finding that Japanese farms that employ climate-controlled greenhouses achieve superior productivity levels compared to open-field setups. Conversely, in tropical regions like Cameron Highlands, efforts to regulate environmental conditions are hampered by high ambient temperatures and humidity, which require sophisticated cooling and dehumidification systems integrated with sensor-based control [3].

Despite the promising advancements, widespread adoption of these smart environmental management systems in tropical lowland areas remains limited due to high investment costs, lack of technical expertise, and infrastructural challenges. There is a critical need to develop cost-effective, scalable solutions tailored for smallholder farmers in these regions. This gap underscores the importance of ongoing research to integrate affordable sensor networks, energy-efficient control systems, and AI algorithms to enable proactive environmental management.

In summary, the challenges facing strawberry cultivation in tropical lowland environments are predominantly driven by climate variability and suboptimal environmental conditions. The adverse effects on yield and quality necessitate the employment of advanced, integrated technologies capable of precise and real-time environmental regulation. The evolving field of smart agriculture offers promising solutions, but further research is needed to optimize these tools for practical, cost-effective application in the unique climatic context of tropical lowlands. These innovations hold the potential not only to stabilize production but also to elevate the economic viability of strawberry farming in these challenging environments. While some of the references cited in this review originate from temperate or subtropical regions, their environmental and technological findings offer valuable insights. These findings are considered adaptable when applied to controlled-environment

agriculture in tropical lowland settings, particularly using smart technologies and automated climate control systems.

Therefore, this review supports the development of an IoT-enabled smart cooling and fertigation system, designed to address microclimate challenges specific to tropical lowland greenhouses. The research and development will be conducted at Politeknik Sultan Haji Ahmad Shah (POLISAS) in Kuantan, leveraging its technical facilities. To evaluate real-world applicability, the system will undergo field testing at FELDA Bukit Sagu 2, a rural community setting, ensuring both technological robustness and relevance to lowland agricultural practices.

2. Environmental Conditions in Strawberry Cultivation

The success of strawberry cultivation in greenhouse systems relies heavily on precise environmental regulation, particularly of temperature, humidity, and lighting conditions. Numerous studies have emphasized the importance of maintaining optimal temperature ranges to maximize growth and fruit quality. A 2020 study by [11]. highlighted the influence of temperature, humidity, light, and CO_2 on strawberry growth and yield under controlled conditions, reinforcing the need to fine-tune these parameters for tropical greenhouse success. Optimal air temperatures between 17°C and 21°C during the day and around 15°C at night have been shown to promote flowering, fruit set, and enhance fruit sweetness and firmness, as reported by [1], [4] and [12]. By referring to the [3] from MARDI cultivation manual, strawberry plants thrive under local day temperatures ranging from 20°C to 28°C and night temperatures between 12°C and 18°C. These broader tropical thresholds reflect Malaysia's climatic reality and provide a practical reference for greenhouse climate control in lowland settings.

According to [12], demonstrated that maintaining root zone temperatures around 25°C (±2°C) significantly improves fruit diameter and weight under tropical conditions. Their findings show that targeted root zone cooling can mitigate heat stress, enhance nutrient uptake, and increase the proportion of marketable fruits. Similarly, [14] highlighted that in lowland tropical regions, controlling both air and root zone temperatures using environmental chambers and sensor-based systems enables consistent production of high-quality strawberries. Their setup employed continuous sensor monitoring and automated adjustments to maintain ideal conditions. These studies collectively underline that in tropical environments, passive approaches such as ventilation and shading are often insufficient; instead, active climate control, guided by real-time sensor feedback, is essential to stabilize growing conditions and optimize yields.

Humidity regulation also plays a vital role in fruit development and disease management. [4] emphasized that optimal relative humidity (RH) levels of around 80% to 90% facilitate healthy flower induction and fruit expansion while minimizing the incidence of fungal diseases like anthracnose. His research demonstrated that fluctuations outside this range particularly high humidity combined with stagnant air could lead to poor fruit quality and increased disease risk. [1] further corroborated that maintaining a consistent RH around 70%–80% during daytime, coupled with temperature control, helps sustain fruit firmness and color. They employed automated humidifiers and dehumidifiers integrated with sensor readings, which allowed real-time adjustments to environmental conditions. Similarly, MARDI researcher [13] advised that relative humidity levels should be kept below 80% to prevent condensation and reduce disease pressure in tropical strawberry greenhouses. Such technological interventions have shown promising results in stabilizing plant performance amidst climatic variability.

Lighting conditions, including supplemental LED lighting, are critical for ensuring sufficient photosynthesis, flowering, and fruiting, especially in regions with inconsistent natural sunlight. [16] provided evidence that increased temperatures during growth stages can be offset by precisely managed supplemental lighting, which enhances photosynthetic efficiency. His experiments indicated that using LED systems with specific spectral compositions primarily red and blue wavelengths could improve plant vigor and fruit quality. [5] extended this understanding by employing IoT-based control systems that dynamically adjust light intensity and duration based on real-time data. Their research introduced a predictive model the RL-Informer integrated with sensor data to optimize both light and temperature, reducing energy consumption while maximizing yield quality. These studies collectively highlight that smart lighting, tailored through digital monitoring, is indispensable in high-tech greenhouse systems.

In addition to temperature, humidity, and lighting, carbon dioxide (CO_2) concentration and nutrient solution electrical conductivity (EC) are critical yet often underexplored factors in optimizing strawberry production in controlled environments. Based on [2] demonstrated that enriching CO_2 to 600 ppm significantly improved photosynthetic rate (by 129.7%), increased intercellular CO_2 concentration (43.7%), and enhanced yield per plant by over 40% compared to ambient conditions. Additionally, CO_2 enrichment was linked to improvements in fruit quality traits such as total soluble solids and vitamin C content, reinforcing the physiological importance of gas-phase optimization under greenhouse conditions.

Complementary to this, nutrient solution EC plays a key role in hydroponic systems. [4] found that an EC level of 1.8 dS/m produced the highest total and marketable yields for the 'Elsanta' cultivar in deep tank hydroponics,

while higher EC levels (2.5 and 4.0) led to reduced biomass and root development due to stress-induced water uptake limitations. In tropical fertigated systems, [13] recommends maintaining nutrient solution EC between 0.8 and 1.5 dS/m to ensure optimal nutrient uptake while avoiding salt accumulation and osmotic stress. This suggests that maintaining optimal EC not only ensures nutrient availability but also prevents physiological stress, which is crucial for maximizing strawberry yield and quality in controlled environments.

Airflow and ventilation play a crucial role in maintaining a stable greenhouse microclimate, especially in tropical lowland environments where heat and humidity fluctuate rapidly. A study by [8] investigated the use of a wind duct and ventilation fan system in a small walk-in strawberry greenhouse in Japan. Their setup, which activated ventilation based on temperature thresholds (~25 °C), successfully stabilized internal air temperatures and reduced humidity peaks. The controlled airflow not only improved the thermal environment but also supported better fruit set and reduced the occurrence of moisture-related diseases. These findings underscore the importance of integrating simple, cost-effective ventilation strategies such as exhaust fans, ducted air channels, and sensor-based triggers into tropical greenhouse designs. In regions where full climate control may be economically challenging, such hybrid ventilation systems provide a practical middle ground between passive and fully automated systems.

In specific studies focusing on the quantitative parameters, [16] emphasized the importance of daily light integral (DLI) and photosynthetically active radiation (PAR) management. They demonstrated that maintaining PAR levels between 387–437 $\mu mol\cdot m{-2}\cdot s{-1}$ under controlled conditions ensured optimal growth without photoinhibition. Shading techniques using photovoltaic modules can help modulate solar radiation, preventing excessive heat buildup and light intensity, which are common in tropical regions. Such strategies not only improve plant health but also contribute to energy savings.

These findings form the foundation for the proposed smart greenhouse system, where real-time sensors and automation will regulate humidity, light, air temperature, and root zone cooling via a solar-powered chiller system. The environmental parameters reviewed here directly inform the control logic to be implemented via an ESP32-based IoT platform in the prototype development.

Table 1 summarizes the optimal environmental parameters for strawberry cultivation in tropical greenhouse systems based on current literature.

Table 1 *Environmental parameters for strawberry cultivation*

Parameter	Optimal Range	Effects	Source(s)
Air Temperature (Day)	17°C – 21°C	Promotes flowering and fruit set	[1], [12]
	20°C – 28°C		[13]
Air Temperature (Night)	~15°C	Enhances sweetness and firmness	[4]
	12°C – 18°C		[13]
Root Zone Temperature	23°C – 25°C ±2°C	Improves nutrient uptake and marketable fruit rate	[10],[14]
Relative Humidity (RH)	70% – 90%	Supports fruit development, reduces fungal diseases	[4]; [1]
	<80%		[13]
CO_2 Concentration	600 ppm	Enhances photosynthesis and yield	[2]
Electrical Conductivity (EC)	1.8 dS/m	Maximizes yield and root health	[4]
	0.8 – 1.51 dS/m		[13]
Light Intensity (PAR)	387–437 $\mu mol\cdot m^{-2}\cdot s^{-1}$ (with red/blue LED support)	Boosts growth, mitigates high heat impacts	[5] , [15], [16]

Parameter	Optimal Range	Effects	Source(s)
Airflow / Ventilation	Temperature-based exhaust fans (~25°C trigger)	Stabilizes internal climate, reduces disease incidence	[8]

3. Smart Technology Integration

The integration of IoT sensor networks and automated control systems has revolutionized strawberry cultivation in controlled environments. As demonstrated in [7], a low-cost smart greenhouse can be built using Arduino microcontrollers and sensors to monitor temperature, humidity, and soil moisture. This setup enabled automated irrigation, cooling, and ventilation, which responded to real-time data to create a stable microclimate conducive to high yield and quality. His system also provided alerts via SMS, reducing manual labor, and ensuring swift responses to environmental fluctuations.

Researcher [6] expanded on this by designing a comprehensive digital monitoring framework that combined soil moisture sensors, temperature loggers, and humidity sensors with machine learning models. Their system used data inputs to predict plant stress and optimize fertigation and cooling schedules, aligned with the model's RL-Informer algorithm. This predictive approach allowed for pre-emptive adjustments, effectively mitigating the adverse impacts of climate variability and resource wastage.

Complementing these, [16] introduced an edge computing-based platform integrating LoRa wireless sensor networks, Raspberry Pi nodes, and computer vision tools. Their use of YOLOv5 for disease recognition and Isolation Forest for anomaly detection achieved over 90% accuracy, enabling rapid and localized responses to environmental or biological threats.

According to [7] that also contributed a tropical-focused IoT framework using NodeMCU, DHT11, and soil moisture sensors to monitor lowland greenhouse conditions. The system connected to a real-time web dashboard, facilitating remote supervision and decision-making for small-scale Malaysian farms. In a parallel study, [18] and [19] demonstrated ESP32-based systems that automated ventilation and irrigation through sensor data while tracking temperature, humidity, light, and soil moisture. Their work also addressed the importance of user acceptance, highlighting cost, awareness, and ease of use as key adoption barriers for IoT-based strawberry systems.

Additionally, [1] highlighted modular sensor systems that allow easy customization and scaling. [14] demonstrated how root zone temperature (RZT) control via chilled nutrient circulation improved nutrient uptake and fruit yield under lowland heat stress. Continuity in [5], emphasized spectrum-adjusted red-blue LED lighting combined with sensor-based light monitoring for flower stimulation and fruit set.

Predictive models like RL-Informer and artificial neural networks (ANN) further refine microclimate optimization by analyzing multi-layered environmental data and forecasting future conditions. These technologies not only support growth performance but also improve energy efficiency, reduce waste, and promote disease prevention contributing toward sustainable precision farming in tropical regions.

Recent advancements in controlled environment agriculture (CEA) form the foundation for the proposed prototype, which will incorporate sensor-driven fertigation systems, microclimate monitoring, and automated cooling technologies into smart greenhouse applications. Studies have shown that integrating root zone cooling, real-time EC-based fertigation, and IoT-enabled environmental monitoring can significantly improve plant health, water-use efficiency, and yield quality in various horticultural crops, including strawberries. Low-cost microcontrollers like the ESP32 have gained popularity due to their wireless capabilities and compatibility with a wide range of agricultural sensors, making them ideal for resource-limited smallholder farming environments.

Table 2 summarizes the smart technologies for environmental control in strawberry greenhouse cultivation based on current literature.

Table 2 *Smart technologies for strawberry cultivation*

Technology	Function / Application	Effects	Source(s)
IoT Systems & Wireless Networks	Monitor temp, humidity, soil moisture; collect & transmit environmental data	Enables automated cooling, misting, and real-time dashboard alerts	[6],[7]
Automated Controls & Actuators	Control misting, fans, lighting based on threshold data	Maintains optimal growth conditions, reduces manual intervention	[1], [7]
Machine Learning & Prediction	Predict plant stress, optimize fertigation and microclimate with RL-Informer & ANN models	Climate adaptation, efficient resource use, better yield forecasting	[6] , [16]
Root Zone & Environmental Control	Chilled nutrient delivery, modular climate regulation	Enhances nutrient uptake and marketable fruit rate	[10],[14]
Smart Lighting	Supplemental LED lighting (red/blue) during low-light periods	Improves flowering, fruit quality	[5]
Edge Computing & Cloud Platforms	Real-time processing, anomaly alerts, remote access via LoRa and dashboards	Boosts disease prevention, facilitates remote greenhouse management	[16], [18]
Smart Fertigation Systems	Auto-nutrient delivery based on EC and soil moisture	Prevents over-fertilization, supports consistent growth	[20]
Mobile-Integrated IoT	ESP32-Android based automation for ventilation, irrigation, and environmental sensing	Improves user accessibility, supports remote supervision, facilitates smart farming adoption	[7], [18], [19]

4. Additional Insights from Broader Research

4.1 Recap of Environmental Optimization and Benefits

The synthesis of recent research clearly demonstrates that maintaining optimal environmental conditions in greenhouse strawberry cultivation especially in tropical lowland regions relies heavily on the precise regulation of temperature, humidity, and light. Across multiple studies, it has been consistently shown that maintaining daytime temperatures around 17°C to 21°C, with night temperatures near 15°C, fosters vigorous growth, flowering, and fruiting [4],[12]. Similarly, optimal humidity levels between 80% and 90% reduce physiological stress and disease incidence, providing a stable microclimate that enhances fruit quality.

These findings align with practices in temperate greenhouse systems but underscore the need for tailored adaptations in tropical lowlands, where ambient conditions are significantly more variable. In such settings, strategies like root zone cooling, enhanced air circulation, and the use of shading systems (e.g., photovoltaic

modules) become essential. Studies have demonstrated improvements in fruit size, sweetness, and firmness when environmental variables are carefully regulated [1], [3].

4.2 Smart Technology and Economic Trade-offs

Smart technologies particularly IoT-enabled sensors and automated systems offer promising solutions for overcoming tropical climate challenges. These systems enable real-time environmental monitoring and dynamic adjustment of growing conditions. For example, networks measuring soil moisture, air temperature, and humidity can automatically trigger irrigation, misting, or cooling fans, minimizing manual intervention and maintaining stable conditions [6]- [7].

Beyond technical improvements, these innovations bring measurable economic benefits. Research has shown that optimized environmental control via smart systems can increase soluble solids content, fruit size, and overall yield quality [5],[14]. Although initial investment in smart infrastructure may be significant, cost–benefit analyses indicate long-term gains through reduced labor, lower water and energy use, and decreased crop losses. These outcomes are especially important in tropical lowlands, where environmental instability often leads to inconsistent production and reduced profitability.

To further improve economic viability, integrating renewable energy sources such as solar panels can reduce operational costs. Energy-efficient systems and smart lighting (e.g., red-blue LED arrays) contribute not only to sustainable operation but also to enhanced plant physiological responses, helping to achieve consistency and quality in production even under challenging conditions.

4.3 Development of Smart Cooling Systems for Lowland Greenhouse Strawberry Cultivation

Building on the environmental and technological insights from preceding sections, this segment focuses on the tailored development of a smart cooling system for lowland strawberry greenhouses. In tropical lowland climates, cooling is one of the most critical yet challenging components in ensuring successful strawberry cultivation within greenhouses. Traditional ventilation and shading methods are often inadequate due to persistently high ambient temperatures that exceed the crop's optimal range. To address this, the present research focuses on the development and deployment of a smart microclimate cooling system tailored specifically for strawberry greenhouses in tropical lowland conditions such as Kuantan, Malaysia.

Among the most promising interventions is the integration of solar-powered root zone chillers, automated misting, and smart fertigation systems that dynamically adjust nutrient delivery based on EC readings. Coordinated via an ESP32-based control architecture, these components form a low-cost, flexible cooling strategy that combines air temperature management and root zone control. The design targets optimal internal greenhouse conditions between 20°C to 28°C during the day and 15°C to 18°C at night as recommended by [12] and [13]. The key innovations in the system include:

- Dual-layer cooling: Air cooling through ventilation and misting; root zone temperature control via chilled nutrient circulation.
- Dynamic automation: Real-time environmental data triggers specific modules (e.g., chiller activation when internal temperatures exceed 28°C).
- Redundancy and reliability: A secondary chiller and a Raspberry Pi-based backup system ensure uninterrupted operation and cloud-based alerts.
- Modular and scalable design: Suitable for small- to medium-scale lowland farmers with potential for wider adoption.

Preliminary simulations from prior studies suggest that a similar system could potentially reduce internal greenhouse temperatures by 4°C–6°C and stabilize root zone temperatures within ±2°C of the target range. These findings are consistent with previous work by [10] and [14], which demonstrated enhanced strawberry yield and sweetness under controlled root zone environments. Future development will explore the integration of machine learning algorithms for predictive microclimate control, optimizing energy usage while enhancing plant response.

The proposed research and development activities will be conducted at Politeknik Sultan Haji Ahmad Shah (POLISAS) in Kuantan, leveraging its facilities and technical expertise. To validate real-world performance, field testing will be carried out at FELDA Bukit Sagu 2, a rural farming community representative of typical lowland agricultural conditions. This dual-site approach ensures both technological robustness and practical relevance to end users.

4.3.1 System Architecture Overview

To operationalize the smart cooling concept, the proposed system architecture is composed of modular components engineered for flexibility, efficiency, and low-cost deployment. A solar energy system powers the core

ESP32 microcontroller, which receives real-time input from environmental sensors that measure temperature, humidity, light intensity, CO_2 levels, and the electrical conductivity (EC) of the nutrient solution. These data points inform automated actuation of root zone chillers, misting units, ventilation fans, and nutrient dosing pumps to optimize the internal greenhouse microclimate. Sensor data are transmitted via Wi-Fi for cloud-based monitoring, alerts, and logging. For system redundancy and offline control, a secondary Raspberry Pi unit is incorporated as a backup controller.

4.3.2 Design Constraints and Challenges

Designing a reliable cooling system for lowland strawberry greenhouses involves multiple technical and practical challenges. High ambient temperatures require a solution capable of reducing internal conditions by 5–10°C while also ensuring stable root zone temperatures to avoid plant stress. Given the rural context, reliance on solar energy is essential, yet poses complexity in managing energy storage and load balancing during cloudy periods or nighttime operation. Furthermore, the system must be robust enough to perform under variable weather, while being affordable and easily maintainable by smallholder farmers with minimal technical training. These challenges necessitate an integrated design that prioritizes modularity, efficiency, and simplicity characteristics embedded in the system architecture detailed in Section 4.3.1.

4.3.3 Testing Metrics and Success Indicators

To evaluate the effectiveness of the proposed system, several performance metrics will be tracked: internal air temperature reduction (targeting 25°C), root zone temperature stability (±2°C), relative humidity maintenance between 70%–85%, consistent EC regulation based on fertigation needs, and real-time operational responsiveness. Additionally, plant performance indicators such as fruit size, sweetness (Brix level), and number of viable runners will be monitored. Energy efficiency and daily solar consumption rates will also be benchmarked.

4.3.4 Prototype Phases and Validation

The development and validation of the proposed smart cooling system will proceed through four structured phases:
- Conceptual Design – Informed by an extensive literature review and environmental benchmarks, this phase defines key components and functional targets.
- System Assembly and Integration – Construction and configuration of the prototype will be carried out at Politeknik Sultan Haji Ahmad Shah (POLISAS), leveraging its facilities and technical expertise.
- Pilot Field Deployment – The prototype will be installed and operated at FELDA Bukit Sagu 2 to assess real-world performance under typical lowland farming conditions.
- Evaluation and Iteration – Data on system performance, crop response, and energy usage will be collected for analysis, with feedback loops to refine system functionality and resilience.

This phased approach ensures the resulting prototype is both technically robust and practically applicable to smallholder farming contexts.

5. Conclusion

Strawberry cultivation in Malaysia's tropical lowlands is hindered by suboptimal environmental conditions that compromise yield and fruit quality. This review has highlighted the importance of precise microclimate management, particularly in regulating temperature, humidity, and root zone stability. Building on these insights, this review proposes a smart greenhouse framework to guide the future development of a system integrating solar-powered root zone chillers, automated fertigation systems, and real-time environmental monitoring using ESP32-based IoT architecture.

The proposed system will be developed and tested at Politeknik Sultan Haji Ahmad Shah (POLISAS) and validated under real-world conditions at FELDA Bukit Sagu 2, a representative rural farming community. This dual-site approach is intended to explore potential improvements in strawberry size, sweetness (Brix), consistency, and resource efficiency.

The novelty of the system lies in its modular, low-cost design, tailored for smallholder adoption in tropical climates. Beyond academic contribution, the solution has the potential to be scaled nationwide through collaboration with research agencies, agri-tech startups, and vocational training institutions. Ultimately, it supports Malaysia's national agenda for sustainable agriculture, food security, and digital farming transformation.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: **Study conception and design:** *Ahmad Zairi Bin Mohd Zain, Nor Sukor Bin Ali;* **Data collection:** *Norazleen Binti Tasuki;* **Analysis and interpretation of results:** *Ahmad Zairi Bin Mohd Zain, Nor Sukor Bin Ali, Nurulain Binti Ahmad;* **Draft manuscript preparation:** *Norazleen Binti Tasuki, Mohd Zulhilmi Bin Jaafar. All authors reviewed the results and approved the final version of the manuscript.*

References

[1]   Shamsudin, R., Hamzah, H., Shuso, K., Yasunaga, E., & Kamarul Zaman, A. A. (2020). A comparison of strawberry cultivation: Case study of selected farms in Malaysia and Japan. International Journal of Academic Research in Business and Social Sciences, 10(1), 232–250. https://doi.org/10.6007/IJARBSS/v10-i1/6847

[2]   Osman, M., Qaryouti, M., Alharbi, S., Alghamdi, B., Al-Soqeer, A., Alharbi, A., Almutairi, K., & Abdelaziz, M. E. (2024). Impact of CO_2 enrichment on growth, yield and fruit quality of F1 hybrid strawberry grown under controlled greenhouse condition. Horticulturae, 10(9), 941.

[3]   Setiawan, A., Maulana, A., & Wardika. (2018). Pengaruh rekayasa iklim terhadap pertumbuhan tanaman stroberi di dataran rendah. Jurnal Teknologi Terapan, 4(1),

[4]   Bagale, K. V. (2018). The effect of electrical conductivity on growth and development of strawberries grown in deep tank hydroponic systems, a physiological study. Journal of Pharmacognosy and Phytochemistry, 2018(1), 1939–1944.

[5]   Lu, Y., Gong, M., Li, J., & Ma, J. (2023). Optimizing controlled environmental agriculture for strawberry cultivation using RL-Informer model. Agronomy, 13, 2057. https://doi.org/10.3390/agronomy13082057

[6]   Jyoti, T., Vivek, C., Ambica, P., & S. M. (2023). Enhancing strawberry cultivation through IoT: A leap towards sustainable smart farming. Proceedings of the 2023 International Conference on Smart Agriculture Technologies.

[7]   Elzenano, J. J., Warner, A. J., Cariaga, R. M., Dela Vega, C. A. C., Gomez, R. M. V., Oranza, J. C., & Samaniego, M. L. B. (2021). Smart farming for lowland strawberry (Fragaria x ananassa) production. Turkish Journal of Computer and Mathematics Education, 12(3), 1797–1804. https://doi.org/10.17762/turcomat.2021.935

[8]   Khammayom, K., Eua-arporn, B., & Chanchai, S. (2022). The effect of climatic parameters on strawberry production in a small walk-in greenhouse. AgriEngineering, 4(1), 109–124. https://doi.org/10.3390/agriengineering4010007

[9]   Unnikrishnan, P., Ponnambalam, K., & Karray, F. (2024). Influence of regional temperature anomalies on strawberry yield: A study using multivariate copula analysis. Sustainability, 16(3523), 1–16. https://doi.org/10.3390/su16093523

[10] Munirah, M., Abdullah, S. A., Kassim, R., Masnira, M. Y., Sakinah, I., Ahmad, M. A., & Tajidin, N. E. (2024). Effects of root zone temperature and light intensity on plant growth, flowering and fruit quality of plant factory 'Festival' strawberry (Fragaria x ananassa Duch.). Food Research, 8(4), 72–78. https://doi.org/10.26656/fr.2017.8(S4).5

[11] H. S. Sim, D. S. Kim, M. G. Ahn, S. R. Ahn, and S. K. Kim, "Prediction of strawberry growth and fruit yield based on environmental and growth data in a greenhouse for soil cultivation with applied autonomous facilities," Horticultural Science and Technology, vol. 38, no. 6, pp. 840–849, 2020, doi: 10.7235/HORT.20200076 .

[12] Naphrom, D., Santasup, C., Panchai, W., Boonraeng, S., & Promwungkwa, A. (2025). The effect of root zone cooling on the growth and development of strawberry (Fragaria × ananassa) in a tropical climate. International Journal of Plant Biology, 16, 54. https://doi.org/10.3390/ijpb16020054

[13] Mohd Ridzuan Mohd Saad, Mohammad Abid Ahmad, Saiful Zaimi Jamil, Roslina Ali, Ahmad Tarmizi Sapii, Mahamud Shahid, Mohamad Abd Manas, & Wan Abdullah Wan Yusoff. (2011). Manual teknologi penanaman strawberi secara fertigasi. Institut Penyelidikan dan Kemajuan Pertanian Malaysia (MARDI).

[14] Mat Sharif, I., Seng Teik, T., Syaifudin, M., & Maslinda, M. S. (2018). Innovation in controlled environment greenhouse (CEGH) for high value temperate crop production in lowland tropics. MSAE Conference Proceedings.

[15] Menzel, C. (2021). Higher temperatures decrease fruit size in strawberry growing in the subtropics. Horticulturae, 7(34), 1–10. https://doi.org/10.3390/horticulturae7020034

[16] Tang, Y., Yu, M., Liang, Y., Li, T., & Zhang, Y. (2020). The effect of temperature and light on strawberry production in a solar greenhouse. Solar Energy, 208, 189–199. https://doi.org/10.1016/j.solener.2020.08.064

[17] Cruz, S., Oliveira, A., Almeida, A., Rodrigues, A., & Figueiredo, R. (2022). Smart strawberry farming using edge computing and IoT. Procedia Computer Science, 210, 568–575. https://doi.org/10.1016/j.procs.2022.11.077

[18] I. N. Sukarma, I. W. R. Ardana, I. G. P. M. E. Putra, I. M. Adi Yasa, and I. M. Purbhawa, "Watering strawberry (Fragaria × ananassa) plants in a greenhouse using IoT-based drip irrigation," *J. Comput. Sci. Technol. Stud.*, vol. 4, no. 1, pp. 72–79, 2022, doi: 10.32996/jcsts.2022.4.1.9.

[19] J. Varela-Aldás, A. Gavilanes, N. Velasco, C. Del-Valle-Soto, and C. Bran, "Acceptance of an IoT system for strawberry cultivation: A case study of different users," Sustainability, vol. 16, no. 16, art. 7221, 2024, doi: 10.3390/su16167221.

[20] Bhuiyan, M. A., Uddin, M. J., Sultana, N., Hoque, A., & Anwar, M. R. (2024). Enhancing strawberry cultivation through IoT: A leap towards sustainable smart farming. IOP Conference Series: Earth and Environmental Science, 1173(1), 012055. https://doi.org/10.1088/1755-1315/1173/1/012055